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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G01N 21/17 A1

(11) International Publication Number: WO 99/01747

(43) International Publication Date: 14 January 1999 (14.01.99)

(21) International Application Number: PCT/US98/11869

(22) International Filing Date: 8 June 1998 (08.06.98)

(30) Priority Data:
08/887,865 3 July 1997 (03.07.97) US

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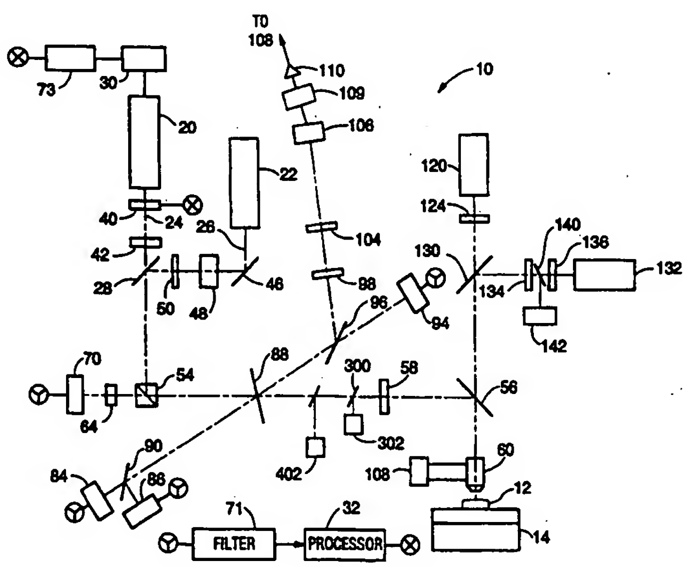
(81) Designated States: JP, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: APPARATUS FOR EVALUATING METALIZED LAYERS ON SEMICONDUCTORS



(57) Abstract

An apparatus for characterizing multilayer samples is disclosed. An intensity modulated pump beam is focused onto the sample surface to periodically excite the sample. A probe beam is focused onto the sample surface within the periodically excited area. The power of the reflected probe beam is measured by a photodetector. The output of the photodetector is filtered and processed to derive the modulated optical reflectivity of the sample. Measurements are taken at a plurality of pump beam modulation frequencies. In addition, measurements are taken as the lateral separation between the pump and probe beam spots on the sample surface is varied. The measurements at multiple modulation frequencies and at different lateral beam spot spacings are used to help characterize complex multilayer samples. In the preferred embodiment, a spectrometer is also included to provide additional data for characterizing the sample.

AT

APPARATUS FOR EVALUATING METALIZED LAYERS ON SEMICONDUCTORS

Technical Field

The subject invention relates to a method and apparatus particularly suited for the nondestructive characterization of opaque layer structures on semiconductor samples.

Background of the Invention

There is a great need in the semiconductor industry for metrology equipment which can provide high resolution, nondestructive evaluation of product wafers as they pass through various fabrication stages. In recent years, a number of products have been developed for the nondestructive evaluation of semiconductor samples. One such product has been successfully marketed by the assignee herein under the trademark Therma-Probe. This device incorporates technology described in the following U.S. Patents: 4,634,290; 4,646,088; 5,854,710 and 5,074,669. The latter patents are incorporated herein by reference,

In the basic device described in the patents, an intensity modulated pump laser beam is focused on the sample surface for periodically exciting the sample. In the case of a semiconductor, thermal and plasma waves are generated in the sample which spread out from the pump beam spot. These waves reflect and scatter off various features and interact with various regions within the sample in a way which alters the flow of heat and/or plasma from the pump beam spot.

The presence of the thermal and plasma waves has a direct effect on the reflectivity at the surface of the sample. Features and regions below the sample surface which alter the passage of the thermal and plasma waves will therefore alter the optical reflective patterns at the surface of the sample. By monitoring the changes in reflectivity of the sample at the surface, information about characteristics below the surface can be investigated.

Semiconductor fabrication technology is increasing in complexity at a rapid pace. Various multilayer structures are being developed which makes testing more difficult. In addition, manufacturers are seeking to increase yields by fabricating chips on larger diameter wafers. As the diameter of the semiconductor wafers increases, the cost and value of each wafer increases. When using large, valuable and expensive wafers, it is no longer economically viable for manufacturers to rely on any forms of destructive testing methodologies. Therefore, there is a great need to provide equipment which can characterize complex structures with many unknowns or variables in a nondestructive manner.

Inspection problems also arise where metalized layers are deposited on semiconductors. If a typical metal layers is more than 100 angstroms thick, it will generally be opaque to more commonly used optical wavelengths. Therefore, equipment designed to monitor relatively transparent oxide layers cannot be effectively used to inspect metalized layers. Therefore, some new methodologies are required in order to inspect semiconductors with metalized layers. These layers can be formed from materials, such as aluminum, titanium, titanium nitride (TiN) and tungsten silicide (WSi).

Summary of the Invention

In order to obtain sufficient information to characterize more complex samples, a system has been developed which substantially increases the amount of data that can be collected. The system of the subject invention includes an intensity modulated pump laser beam which is focused onto the sample in a manner to periodically excite the sample. A probe laser beam is focused onto the sample within the periodically heated area. A photodetector is provided for monitoring the reflected power of the probe beam and generating an output signal responsive thereto. The output signal is filtered and processed to provide a measure of the modulated optical reflectivity of the sample.

In the preferred embodiment of the subject invention, further information can be obtained by varying the modulation frequency of the pump beam. While it has been known that obtaining information as a function of modulation frequency is useful, the subject invention expands upon the past teachings by increasing the modulation range. In particular, in the prior art, the modulation range was typically in the 100 KHz to 1 MHz range. Some experiments utilized modulation frequency as high as 10 MHz. In the subject device, it has been found useful to take measurements with modulation frequencies up to 100 MHz range. At these high frequencies, the thermal wavelengths are very short, enabling information to be obtained for thin metal layers on a sample, on the order of 100 angstroms.

In the preferred embodiment of the subject invention, further information can be obtained by varying the spot sizes of either the pump or probe beams. Varying the spot size of the pump beam will vary the propagation characteristics of the thermal waves. Varying the spot size of the probe beam will vary the sensitivity of the system with respect to the depth of detection. By taking measurements at different spot sizes, some depth profiling information can be recorded and used to characterize the sample.

In the preferred embodiment of the subject invention, still further information can be derived by obtaining independent reflectivity measurements at a plurality of wavelengths. More specifically, the subject apparatus can further include a polychromatic light source generating a second probe beam which is directed to the sample surface. The reflected beam is captured by a detector which is capable of measuring power as a function of wavelength. These added measurements can also be used to help better resolve ambiguities in the analysis and improve the characterization of the sample.

It is also possible to add additional measurement modules which measure either reflectivity or ellipsometric parameters as a function of angle

Gas, solid state or semiconductor lasers can be used. As described in the assignees earlier patents, other means for exciting the sample can include different sources of electromagnetic radiation or particle beams such as from an electron gun.

In the preferred embodiment, semiconductor lasers are selected for both the pump and probe lasers due to their reliability and long life. In the illustrated embodiment, pump laser 20 generates a near infrared output beam 24 at 790nm while probe laser 22 generates a visible output beam 26 at 670nm. Suitable semiconductor lasers for this application include the Mitsubishi ML6414R (operated at 30mW output) for the pump laser and a Toshiba Model 9211 (5 mW output) for the probe laser. The outputs of the two lasers are linearly polarized. The beams are combined with a dichroic mirror 28. It is also possible to use two lasers with similar wavelengths and rely on polarization discrimination for beam combining and splitting.

Pump laser 20 is connected to a power supply 30 which is under the control of a processor 32. The output beam of laser 20 is intensity modulated through the output of power supply 30. The modulation frequency has a range running from 100 KHz to 100 MHz. In the preferred embodiment, the modulation frequency can be set up to 125 MHz. As described in the above cited patents, if an ion laser is used to generate the pump beam, the intensity modulation can be achieved by a separate acousto-optic modulator.

Prior to reaching the beam combining mirror 26, the probe beam 24 passes through a tracker 40 and a shutter 42. Tracker 40 is used to control the lateral position of beam 24 with respect to the probe beam as discussed more fully hereinbelow. The shutter 42 is used to block the pump beam when other measurements which do not require periodic excitation are being taken.

The beam 26 from probe laser 22 is turned by mirror 46 and passed through a collimator 48 which is used to match the focal plane of the probe

reflected probe beam which are synchronous with the pump beam modulation frequency. In the preferred embodiment, the filter 71 includes a lock-in detector 72 for monitoring the magnitude and phase of the periodic reflectivity signal. Because the modulation frequency of pump laser can be so high, it is preferable to provide an initial down-mixing stage for reducing the frequency of detection.

A schematic diagram of the frequency generation and detection stage is illustrated in Figure 2. As shown therein, a frequency synthesizer 73 is provided for generating the various pump beam modulation frequencies. Synthesizer 73 is under the control of processor 32 and can generate an output from 100 KHz to at least 125 KHz. This output is delivered as a signal to the power supply 30 of laser 20.

Synthesizer 73 also generates an electronic heterodyne signal for delivery to the lock-in amplifier 72. The heterodyne signal will be close to, but different from the signal sent to the pump laser. For example, the heterodyne signal can be 10 KHz higher than the signal sent to the pump laser.

The heterodyne signal from the synthesizer is combined with the output from the signal detector 70 in a mixer 74. The output of the mixer will include signal components at both the sum and difference of the two input signals. The difference signal will be at the relatively low frequency of 10 KHz. All the signals are passed through a low pass filter 75 to eliminate the high frequency components from the synthesizer and the detector. The low frequency signal is then demodulated by demodulator 76. The outputs of demodulator 76 are the "in-phase" and "quadrature" signals typical of a lock-in amplifier. The in-phase and quadrature signals can be used by processor 32 to calculate the magnitude and the phase of the modulated optical reflectivity signal.

In initial experiments, a model SR844 lock-in detector from Stanford Research Systems was utilized. This device utilizes a combination of analog and digital techniques to permit operation over a wide frequency range. In

of the pump and probe lasers are monitored by incident power detectors 84 and 86 respectively. A wedge 88 functions to pick off about one percent of the incident beam power and redirects it to an edge filter 90 for separating the two beams. The outputs of the detector 84 and 86 are passed through the low pass portion of filter 71 and into the processor 32.

The signals are further normalized by taking a measurement of the power of the pump beam 24 after it has been reflected. This measurement is used to determine the amount of pump energy which has been absorbed in the sample. The pump beam reflected power is measured by detector 94. Wedge 88 functions to pick off about one percent of the returning beams which are redirected to edge filter 96. The DC signal for both the incident pump and probe beam powers as well as the reflected beam powers are used to correct for laser intensity fluctuations and absorption and reflection variations in the samples. In addition, the signals can be used to help calculate sample parameters.

An autofocus mechanism is used to maintain the spacing between the objective 60 and the sample 12 to be equal to the focal length of the objective. This distance can be maintained to less than one hundredth of a micron.

The autofocus mechanism includes a servo motor 108 for varying the vertical position of the objective 60. The servo is driven by an analog detection loop which determines if the objective 60 is properly focusing the probe beam. As seen in Figure 1, a small portion of the reflected probe beam light picked off by the wedge 88 is redirected by filter 96 into the main elements of the autofocus detection loop. The probe beam is focused by a lens 98 through a chopper wheel 104 located in the focal plane of the lens 98. The light passing the chopper wheel 104 is imaged on a split-cell photodetector 106.

If the objective 60 is out of focus, there will be a phase difference in the light striking the two sides of the split cell detector 106 which is measured by a phase detector 109. The phase difference is used as an input

modulation frequencies and the number of frequencies is selected by the operator. As noted above, in the preferred embodiment, the range of pump beam modulation frequencies covers from 100 KHz to 125 MHz. The output from the photodetector 70 is passed through the filter 71 (including lock-in 72) to the processor which records the magnitude and/or phase of the modulated optical reflectivity signal for each of the modulation frequencies selected.

In accordance with the subject invention, once the desired measurements are completed with the beam spots in an overlapping, aligned position, the processor signals the tracker 40 to adjust the position of the pump beam 24 so that pump and probe beam spots on the sample surface are laterally displaced. In one possible scenario, the beams are initially displaced a distance of one micron. Once in this position, a series of measurements are taken at different modulation frequencies in the manner described above. Once again, the processor will record the modulated optical reflectivity signal at each of these modulation frequencies.

In accordance with the subject invention, once the second set of measurements are complete, the processor will again command the tracker 40 to further separate the pump and probe beam spots to a distance of two microns. Measurements will then be taken at this two micron spacing and at subsequent spacings, each time increasing the spacing by one micron. It is envisioned that for complex samples, measurement might be taken at successive increments of 0.5 microns. Alternatively, measurements can be taken as the separation of the two beam spots is continuously increased. The span of spacings between beam spots can range from overlapping to about 10 microns.

It is envisioned that the user will be able to determine what sort of scanning algorithm is best suited to the particular test situation. Variables such as separation distance and number of measurements at each separation can be entered by the user through a software interface.

3-dimensional character of the thermal waves. This variation in the generation and detection characteristics of thermal waves is characterized by the square root of the sum of the squares of the pump and probe beam diameters. When this value is small compared to the thermal diffusion length, the measurement is 3-dimensional in character and when the value is large compared to the thermal diffusion length, the measurement is 1-dimensional in character. By taking measurements at different pump and/or probe beam spot sizes, some depth profiling information can be recorded and used to characterize the sample.

As noted above, the spot size of both the beams can be controlled by the autofocus system. In order to increase the size of the beam spots, the processor can add an offset to the focusing algorithm which would defocus the beams. The beam spots can be made of different sizes by adjusting the collimator 48. In the preferred embodiment, measurements are taken and recorded at various beam spot sizes ranging from one micron to ten microns. This additional information can be used to characterize the sample.

In the preferred embodiment of the subject invention, still further measurements can be taken to reduce the ambiguities of analysis. More specifically, in addition to the modulated optical reflectivity measurements, it is also desirable to monitor the periodic angular deflections of the probe beam due to deformations in the surface of the sample induced by the periodic heating. This type of measurement is described in detail in U.S. Patent Nos. 4,521,118 and 4,522,510, cited above. As described in those patents, because of the thermal expansion properties of samples, the periodic heating by the pump beam will create a time varying "bump" in the sample surface. If the pump and probe beam are spaced apart, the probe beam will undergo periodic angular deviations at the frequency of the modulated heating. These angular deviations can be measured by a split cell detector. The output of the split cell is sent to the filter and the processor. The

one form of a spectrometer. As seen therein, the white light beam 122 strikes a curved grating 242 which functions to angularly spread the beam as a function of wavelength. A photodetector 244 is provided for measuring the beam. Detector 244 is typically a photodiode array with different wavelengths or colors falling on each element 246 in the array. The outputs of the diode array are sent to the processor for determining the reflectivity of the sample as a function of wavelength. This information can be used by the processor during the modeling steps to help further characterize the sample.

It is also possible to provide a mechanism for measuring sample reflectivity as a function of the angle of incidence of the beam. To achieved this goal, a portion of the reflected probe beam light 26 can be picked off by wedge 300. This light is sent to a beam profile reflectometer module 302 as more clearly shown in Figure 5. When taking these measurements, the pump beam is preferably turned off so that the probe beam will not be modulated.

Module 302 is of the type described in U.S. Patent No. 4,999,014 assigned to the assignee herein and incorporated by reference. As described therein, if a probe beam is focused onto a sample with a strong lens, various rays within the beam will strike the sample surface at a range of angles of incidence. If the beam is properly imaged with a relay lens 306, the various rays can be mapped onto a linear photodiode array 308. The higher angles of incidence rays will fall closer to the opposed ends of the array. The output from each element 309 in the diode array will correspond to different angles of incidence. Preferably, two orthogonally disposed arrays 308a and 308b are provided to generate angle of incidence information in two axes. A beam splitter 310 is used to separate the probe beam into two parts so both axes can be detected simultaneously. The output of the arrays will supplied to the processor 32 for storage. The data can be used to further characterize the sample.

In still a further preferred embodiment, ellipsometric information can be derived from the sample using the reflected probe beam. As in the

As can be seen, the subject device can be used to provide a large amount of measurement data in order to better resolve the characteristics of the sample. Such complete measurements are often necessary in order to determine the composition of a multilayer structure.

While the subject invention has been described with reference to a preferred embodiment, various changes and modifications could be made therein, by one skilled in the art, without varying from the scope and spirit of the subject invention as defined by the appended claims.

5. A method as recited in claim 1 further including the step of varying the modulation frequency of the pump laser and measuring the power of the reflected probe beam at a plurality of modulation frequencies and using the measurements to characterize the sample.

6. A method as recited in claim 5 wherein the modulation frequency of the pump laser beam is varied from 100 KHz to 100 MHz.

7. A method as recited in claim 1 further including the step of varying the size of either of both of the pump and probe laser beam spots on the sample surface and measuring the power of the reflected probe beam at a plurality of pump and probe beam spot sizes and using the measurements to characterize the sample.

8. A method as recited in claim 1 further including the step of measuring the periodic angular deflections of the probe laser beam and using those measurements to evaluate the characteristics of the sample.

9. A method as recited in claim 1 further including the step of measuring the intensity of rays within the probe laser beam as a function of the angle of incidence with respect to the sample surface and using the angle of incidence measurements to evaluate the characteristics of the sample.

10. A method as recited in claim 1 further including the step of measuring the change in polarization state of the reflected probe beam and using the measurements to evaluate the characteristics of the sample.

11. A method as recited in claim 10 wherein the step of measuring the change of polarization state of the reflected probe beam includes generating an output signal that represents an integration of rays within the

measuring the power of the reflected probe beam and generating an output signal in response thereto;

filtering the output signals to provide a measure of the magnitude or phase of the modulated optical reflectivity of the sample;

directing a broadband, polychromatic light beam onto a spot on the surface of the sample;

measuring the intensity of the reflected polychromatic light beam and generating a plurality of second output signals corresponding to a plurality of different wavelengths within the polychromatic beam; and

evaluating the characteristics of the sample using the modulated optical reflectivity measurements and the measurements at different wavelengths.

15. A method as recited in claim 14 further including the step of varying the modulation frequency of the pump laser and measuring the power of the reflected probe beam at a plurality of modulation frequencies and using the measurements to characterize the sample.

16. A method as recited in claim 14 further including the step of varying the size of either of both of the pump and probe laser beam spots on the sample surface and measuring the power of the reflected probe beam at a plurality of pump and probe beam spot sizes and using the measurements to characterize the sample.

17. A method as recited in claim 14 further including the step of varying the separation between pump and probe laser beam spots on the sample surface and measuring the power of the reflected probe beam at a plurality of separations and using the measurements to characterize the sample.

generating an output signal that represents an integration of rays within the probe beam having multiple angles of incidence with respect to the sample surface.

26. An apparatus for evaluating the characteristics of a sample comprising:

an intensity modulated pump laser beam, said pump beam being directed to a spot on the surface of the sample for periodically exciting the sample;

a probe laser beam being directed to a spot on the surface of the sample within a region that has been periodically excited and is reflected therefrom;

a photodetector for measuring the power of the reflected probe beam and generating an output signal in response thereto;

means for adjusting the spot size of either or both of the pump or probe beams on the surface of the sample; and

processor for filtering the output signal to provide a measure of the magnitude or phase of the modulated optical reflectivity of the sample, said processor further functioning to control the spot size adjustment means in a manner so that a plurality of measurements are taken and recorded at a plurality of different spot sizes with the plurality of measurements being used to evaluate the characteristics of the sample.

27. An apparatus as recited in claim 26 wherein the size of the beam spots is varied from a few microns in diameter to ten microns in diameter.

28. An apparatus as recited in claim 26 further including a steering means for adjusting the lateral separation between the pump and probe laser beam spots on the surface of the sample and wherein a plurality of measurements are taken at different separations between the pump and probe

probe beam having multiple angles of incidence with respect to the sample surface.

35. An apparatus as recited in claim 28 further including a broadband polychromatic light source for generating a polychromatic probe beam, said polychromatic probe beam being directed to a spot on the surface of the sample and is reflected therefrom, said apparatus further including a detector means for measuring the power of the reflected polychromatic light beam and generating a plurality of second output signals corresponding to a plurality of different wavelengths within the polychromatic beam and wherein the processor uses the second output signals to evaluate the characteristics of the sample.

36. An apparatus for evaluating the characteristics of a sample, comprising:

an intensity modulated pump laser beam, said pump beam being directed to a spot on the surface of the sample for periodically exciting the sample;

a probe laser beam being directed to a spot on the surface of the sample within a region which has been periodically excited and is reflected therefrom;

a photodetector for measuring the power of the reflected probe laser beam and generating a first output signal in response thereto;

a broadband polychromatic light source for generating a polychromatic probe beam, said polychromatic probe beam being directed to a spot on the surface of the sample and is reflected therefrom;

detector means for measuring the power of the reflected polychromatic probe beam and generating a plurality of second output signals corresponding to a plurality of different wavelengths within the polychromatic probe beam; and

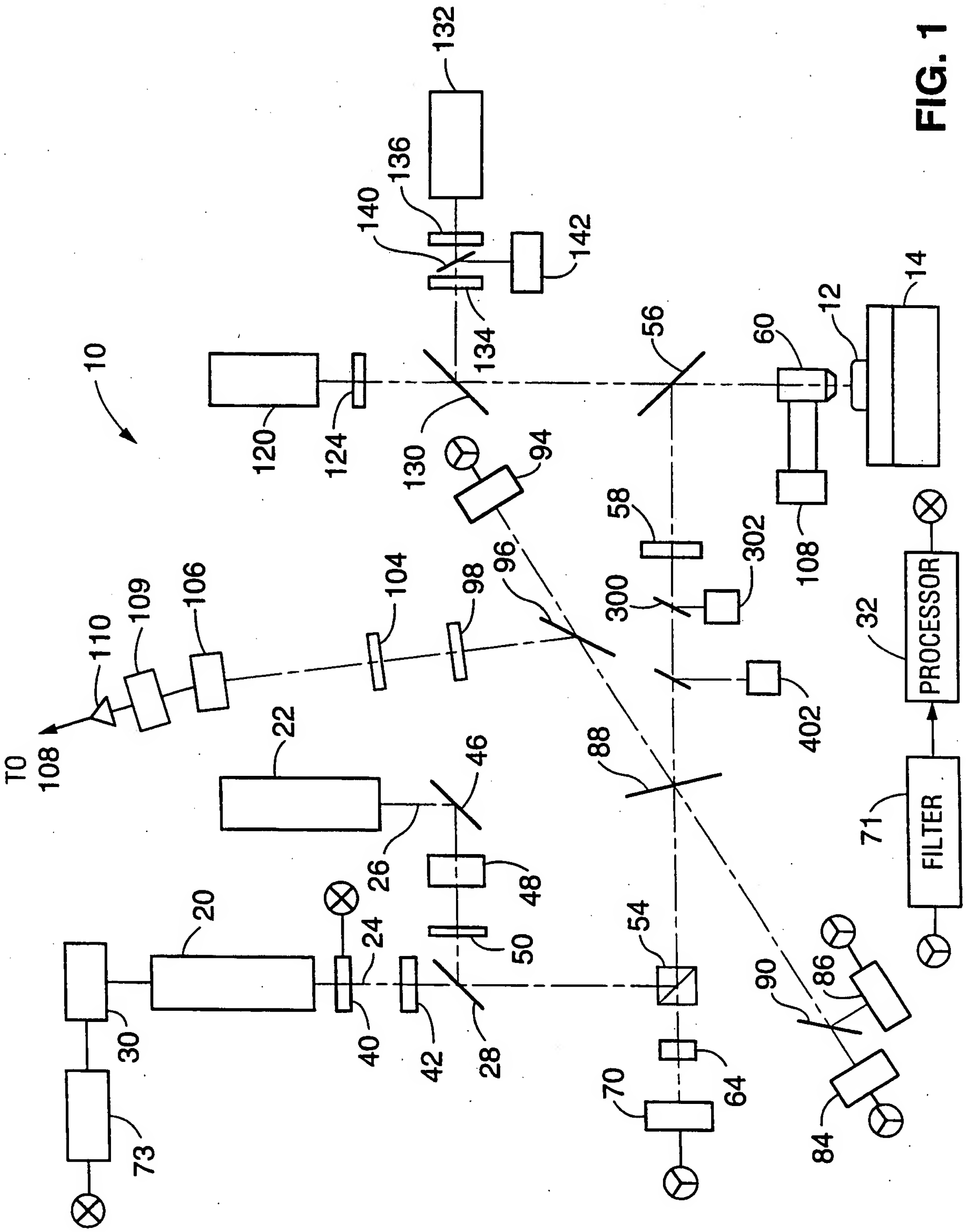
and wherein the reflected power of the probe laser beam is measured as the size of the spots is varied and wherein the processor uses the measurements at different spot sizes to evaluate the characteristics of the sample.

43. An apparatus as recited in claim 38 wherein the photodetector measures the periodic angular deflections of the probe laser beam and wherein the processor uses the angular deflection measurements to evaluate the characteristics of the sample.

44. An apparatus as recited in claim 38 further including a second detector means for measuring the intensity of rays within the probe laser beam as a function of the angle of incidence with respect to the sample surface and wherein the processor uses the angle of incidence measurements to evaluate the characteristics of the sample.

45. An apparatus as recited in claim 38 further including a second detector means for measuring the change in polarization state of the reflected probe beam and wherein the processor uses the polarization state measurements to evaluate the characteristics of the sample.

46. An apparatus as recited in claim 45 wherein the second detector means generates an output signal that represents an integration of rays within the probe beam having multiple angles of incidence with respect to the sample surface.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88
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PROCESSOR
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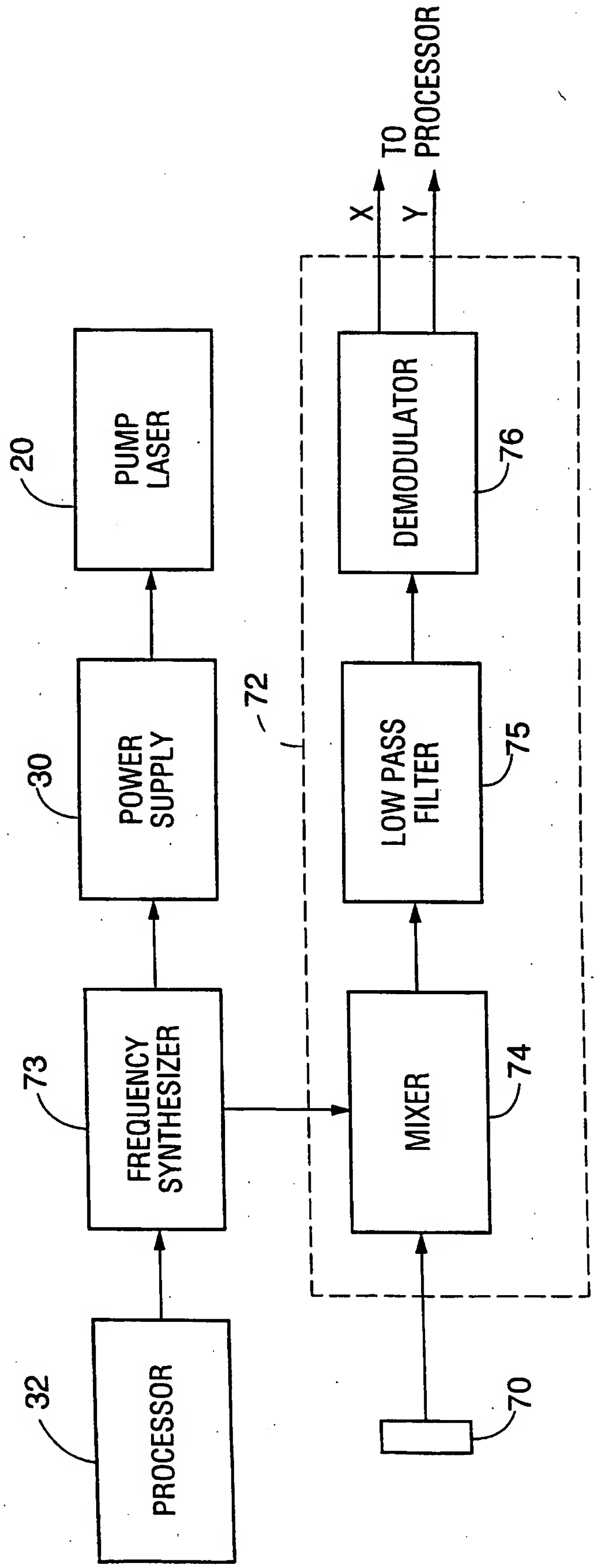
FILTER

FIG. 1


PROCESSOR
32
FREQUENCY SYNTHESIZER
73
POWER SUPPLY
30
PUMP LASER
20
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MIXER
74
LOW PASS FILTER
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DEMODULATOR
76
70
X
Y
TO PROCESSOR

FIG. 2

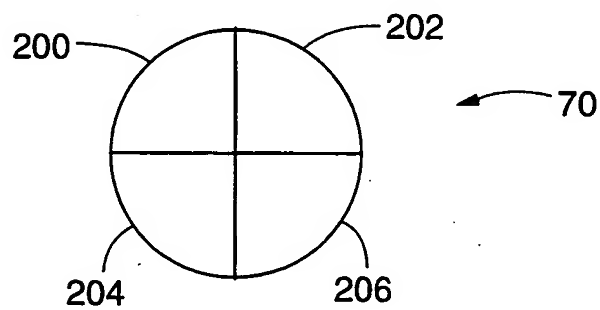

FIG. 3

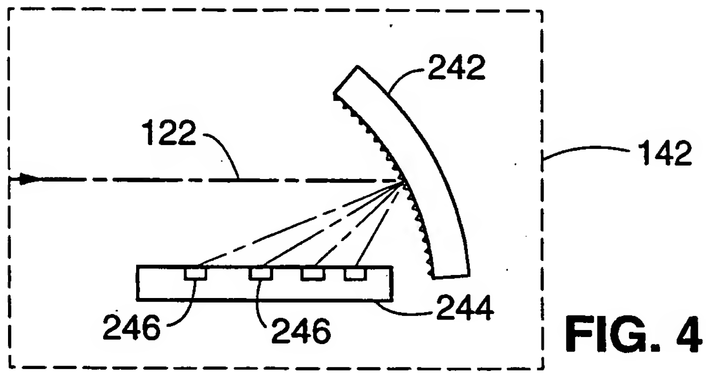

FIG. 4

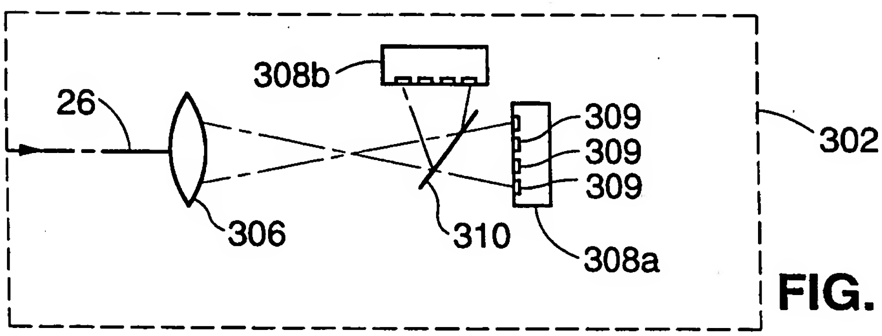

FIG. 5

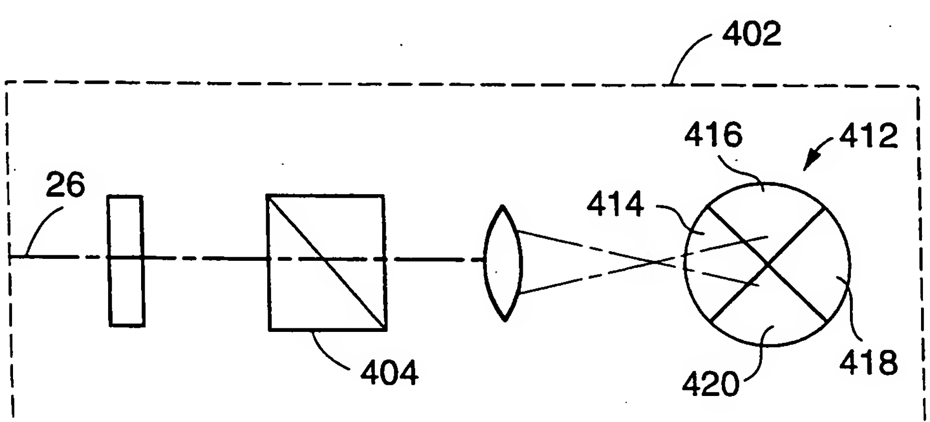

FIG. 6

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/11869

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01N21/17

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 710 030 A (TAUC) 1 December 1987 see column 1, paragraph 1 see column 3, line 21 - line 43 see column 3, line 50 - line 61 see column 4, line 10 - line 12 see column 8, line 2 - line 8 see column 9, line 10 - line 16 see column 13, line 22 - line 39	1,2,10
A	see figures 4,12	6,12,14, 17,18, 26,28, 30,36,41
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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
2 October 1998	13/10/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Thomas, R.M.

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 98/11869

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